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Understanding and Forecasting the Sun's Impact on the Battlespace Environment

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Introduction: The battlespace environment extends far above the surface of the Earth. Of special importance are the outer layers of the Earth's atmosphere, from altitudes 100 to 1000 km, where there is sufficient mass to impede the motion of Earth-orbiting spacecraft, and where layers of charged particles control the propagation of radio waves. Changes in atmospheric "drag" alter the orbits of the thousands of space objects in low Earth orbit (LEO) that are tracked by the U.S. Space Command. The ionosphere transmits, reflects, retards, and refracts kHz to MHz radio wave frequencies. As a result, fluctuations in the neutral and ionized environment can negatively impact Naval operations by disrupting communications and navigation and by degrading radar accuracy, targeting precision, and orbit prediction.

The Sun is the primary source of variations in the neutral and ionized upper atmosphere. A suite of new solar and atmospheric databases that extend over the Sun's 11-year activity cycle are now refining our understanding of the intricately interconnected Sun-Earth system, thereby improving the ability to predict this region's impact on DoD systems. The new databases include solar imagery from NRL instruments aboard the Solar Heliospheric Observatory (SOHO),¹ daily thermospheric mass density derived from spacecraft drag via a new NRL algorithm,² and total electron content obtained from analyses of GPS timing by the Center for Orbit Determination in Europe (CODE).³

Changing Solar EUV Radiation: The Sun's extreme ultraviolet (EUV) radiation waxes and wanes continuously throughout the 11-year solar activity cycle, as bright active regions emerge, evolve, and decay in the outer solar atmosphere. The Sun's rotation on its axis further modulates the EUV radiation on a cycle of approximately 27 days by altering the population of active regions on its hemisphere visible at Earth. The sequence of solar images in Fig. 6, made at 28.4 nm by SOHO's Extreme Imaging Telescope (EIT),¹ illustrates the passage of large active regions across the solar disk. These cycles cause Earth-directed EUV radiation (irradiance) to vary by a factor of ~two over each 27-day period, as shown in Fig. 6(a).

Impacts on the Upper Atmosphere and Ionosphere: Since solar EUV radiation supplies the energy that heats the upper atmosphere and creates the ionosphere, its fluctuations directly impact neutral and ion compositions. Spacecraft in low Earth orbit decay

more rapidly when solar activity is high because the upper atmosphere is hotter and denser. Ionospheric transmission of radio waves decreases because there are more electrons, and higher-frequency radio waves are reflected because peak electron densities are larger.

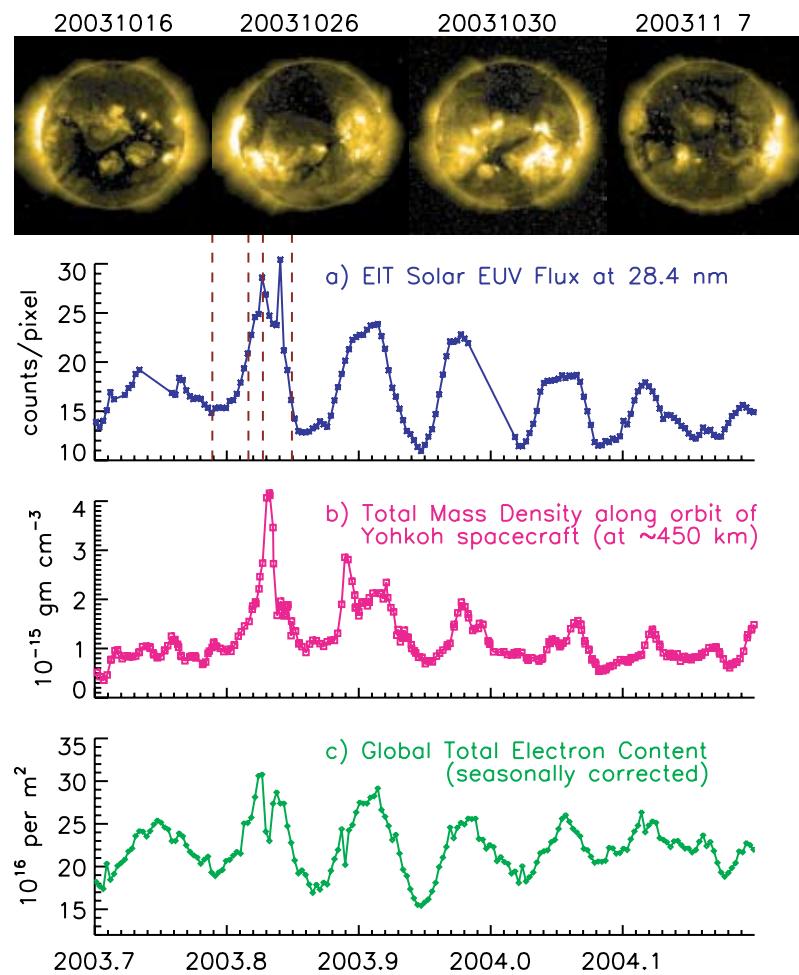
As Fig. 6 illustrates, neutral densities (b) and total electron content (c) change significantly during the Sun's rotational cycle. Along the track of the Yohkoh spacecraft (USSPACECOM object 21694) at about 450 km altitude, mass density (derived from two-line element sets, TLEs, using NRL's new algorithm²) can increase by factors of two, with concomitant increases in spacecraft drag. During the last rotational cycle of 2003, for example, the decay rate of Yohkoh (mass $M = 390$ kg, cross-sectional area $A = 1 \text{ m}^2$) increased from 0.07 km/day to 0.2 km/day. Since drag acceleration is proportional to A/M , the decay rate of a picosat ($M = 0.5$ kg, $A = 0.01 \text{ m}^2$) in a similar orbit would be an order of magnitude larger.

Forecasting Solar EUV Radiation: Because of the impact of space weather on civilian and military space operations, utilization, and assets, the National Weather Service and Air Force Weather Agency jointly issue 1- to 3-day and longer forecasts of the 10.7 cm radio flux. This index of solar EUV radiation is used for input to a variety of space weather models, such as the NRLMSIS⁴ neutral density specification model. Analysis of time series of solar EUV radiation and atmospheric densities, such as in Fig. 6, aid in characterizing and understanding changes in the battlespace environment that are driven by solar activity, and in validating and improving space weather models. Solar imagery such as in Fig. 6 promises to enhance near-term forecasting capability by identifying the impending impact of large active regions that emerge on the Sun's east limb, prior to rotating to the center where their contribution to Earth-directed flux maximizes. Figure 7 shows that the east limb flux leads the net flux by about 5 days.

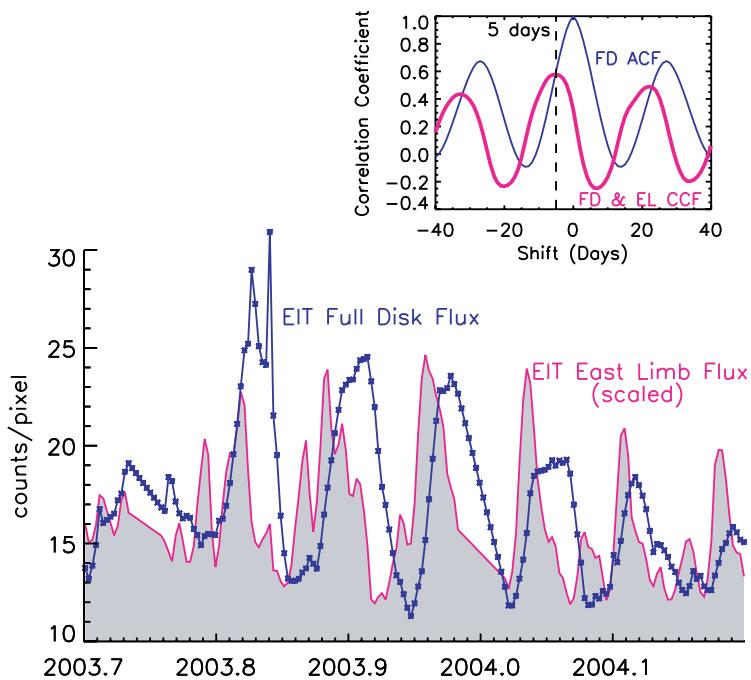
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**FIGURE 6**

Images of the Sun made by SOHO EIT¹ at 28.4 nm show the movement of bright active regions across the Sun's disk as a result of its rotation on its axis. Shown in (a) are the resultant changes in the net solar EUV radiation obtained by summing all pixels in each image during a period of six solar rotations. During the same period, total mass densities in the upper atmosphere estimated along the track of the Yohkoh spacecraft (altitude ~450 km) from TLEs² varied as shown in (b). The total electron content variations shown in (c) are derived from GPS by CODE.³

**FIGURE 7**

The net, disk-integrated solar EUV radiation at 28.4 nm from Fig. 6(a) is compared with the radiation from the east limb (left side of each image in Fig. 6). As the cross-correlation function in the inset figure shows, the east limb (EL) flux peaks approximately five days prior to the full disk (FD) flux.